Physical Models in animation: towards a Modular and Instrumental Approach

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Towards a modular and instrumental approach

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Abstract

Image synthesis has presented itself as an art of the 'observable'. Physical models open the way to a art of "manipulable".

This article presents :

I. A general formalisation for physical objects representation.
We will demonstrate that a physical model :
* achieves a generic definition of movement.
* is intrinsically capable of interaction.
* is in principle manipulable.

II. A physical object "simulator-modeler".
For this, we need :
1. To select a modelisation principle. The choices are related to particle physics, atomic interactions and localized constant decomposition.
2. To choose the "components" of the system, that should insure the completude of the system.
3. To elaborate the assembly criteria , that ensure that each combination is a calculable physical object.
Physical objects can be defined in terms of "interconnected boxes" well adapted to real time implementations.

III. The results and simulations
We will show with some examples, that we can build, simulate, manipulate a large variety of physical objects, currently obtained by different methods :
* high multiplicity physical particles system
* Rigid, plastic and deformable objects in interaction, with collisions, fractures and sticking.
Specific devices, the "16-slice Feedback Touch" and the "Two-twimbles", allows the operator to manipulate these objects and perceive them with touch.

The entire system, named "Cordis-Anima, equipped with the language, the simulator, the gestual devices, and the real time visualisation, constitutes a genuine tool for building, experimenting and perceiving an "artificial reality".

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Key words and expressions

Animation - Physical modeling - Real time simulation - Flexibles objects - Physical interactions - Collisions - Fractures - Modularity - Gestual control - Gestual feedback

I. Introduction

I. 1. From the observable to the manipulable, from the determined to the constructible

Image synthesis, as an aftermath to the "pixel" stage, has followed the natural course of informatics and evolved towards the representation of more integrated entities by the introduction of the idea of object. What we refer to as an object is precisely a perceptible thing to which we may attribute a given structural, perceptual, or manipulatory invariance.

The above leads us to say that image synthesis aims at representing objects according to their visual or spatial appearance. The methods that have been developed, be they representations of volumes, surfaces, texture, behaviour under different lighting, or manipulations associated with these representations such as lighting or viewpoint changes, have meant that the synthesis of images is currently an art of the OBSERVABLE.

However, this means that the objects that are accessible via these representations have the following shortcomings :

1. They do not move.
2. They are rigid.
3. They cannot interact amongst themselves or with their environment.

We might say that they " are merely what they are", except for the fact that they are extremely constructible.
Be that as it may, there are other types of objects in nature, and in contrast these can be typified because they "act".
Hence, the latter :

1. Move.
2. Can be physically manipulated.
3. Can be used to achieve something , and thus interact with other objects.

In order to represent them we have to go further. We must :

1. Introduce intrinsic movement into the representation of objects.
2. Introduce their physical manipulabilty.
3. Introduce their capacity to interact on and with other objects.

In addition, this must be achieved without losing any ground as regards the main breakthrough in informatics, i.e. constructibility and modularity.

It goes without saying that geometric and physical objects are produced that are clearly seen to move. To achieve this, the usual approaches more or less directly describe the movement itself, and belong explicitly or implicitly to a synthesis / analysis methodology of the latter.

The above approaches, that are cinematic, calculate time function trajectories, either by representing them directly by a Positions(t) type of description, that can be algebraic or not, or by means of a procedural process, that is optimised according to the object categories, as for example in a chronological list of geometric transformations.

These methods guarantee that all observable movement may be synthesised.

Although the object that are obtained in this fashion may be mobile, they will nonetheless remain rigid overall ; They are neither manipulable nor in interaction with others.

We therefore have to begin by extending our conception of the object, in order to make it intrinsically mobile, manipulable, and capable of interaction.

To do this, the geometric and visual object has to take physical form.

A physical object is one that possesses a supplementary invariant to those of morphology and visuality : this is an intrinsic behaviour to external stimuli.

Hence, 2 remarks :

1. This lessens the gap between the natural object and the purely geometric or visual object. As in a natural object, a certain autonomy is granted.

2. This behaviour finds expression in an interaction context, for the objects in interaction are necessarily in movement. It follows that manipulable objects are necessarily capable of interaction, and hence manipulability is therefore a sufficient condition of mobility.

I.2. From the determined to the constructible

A recent major current in image synthesis has been developed that is known as "physical modelisation". The main stages are :

* The Sinden film, [Zaj 64] entitled "Force, Mass and Motion",
* The ANIMA system [Luc 81, Luc 84, Luc 85, Raz 86], designed as a modular physical object simulation system,
* The research work carried out by the OSU [Sch 84] that introduces physical calculus as a co-calculation in an animation system based on the principles of conventional animation.

Today, the major research amongst those concerned with the physical simulation of objects in movement is tending towards "numeric calculation in solids, rigid or deformable, physics".

It therefore follows that these are individualised studies, either of specific phenomena such as rigid bodies system, deformability or plasticity, [Ter 87, Ter 88, Bar 88, Pla 88, Arn 88, Dum 89] or of specific algorithm insertion, e.g. collisions within a complete animation system [Hah 88].

We shall follow the lead offered by the Anima system, and we intend to propose a general formalism and adapted calculation methods for a "modeler - simulator" capable of describing and simulating a wide field of physical objects rather than studies of specific uses of physical models.

The characteristics of the formalism and associated calculation methods that we shall introduce here are the following :

1. The intrinsic shape, all types of interactions, and the behaviour of material are taken in charge by a single formalism . Here, unlike the "solids physics" standpoint, interactions play an essential role.

2. Scene or object construction is enabled by the very nature of the models and their associated calculations, and, above all, both are modular.

3. The algorithms lend themselves well to real time calculations. This enables extension of interactions between the simulated objects to those between real objects, be they man or robot.

5. The distance between model description formalism and that of their actual simulation is kept to a minimum, in order to increase the degree of experimentability of the models.

What we intend to propose is a modelisation and physical object simulation language that is firmly rooted in the central notion of "model", which should be understood in its conceptual and operational sense, and not merely in an algorithmic context.

II. Object representation : the physical model

II.1. What is an object or a physical object - the necessary and sufficient condition

A physical object is an object which, when subjected to physical actions - forces or displacements - displaces and deforms itself. Thus, it is necessarily subjected to the two fundamental laws of dynamics, namely an action - reaction principle and to movement quantity conservation.

Several consequences result from this :

1. A physical object generates movements
2. It is manipulable. Actions can be applied to it.
3. It is capable of interaction.
4. It is "in action" - it can act and react (autonomy)
5. It can be perceived by other senses than sight, and in particular, by touch.

A physical model is a physical object ; it satisfies the former condition.

According to this definition :

- An object from the natural world is a physical object.
- A photograph of a natural object is a model of this object, but does not constitute a physical model.
- A scale model of this natural object - a physical reproduction - is a physical model of a physical object.

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- A programme that calculates all the physical behaviour of the natural object in response to physical actions is a physical model of a physical object...

II. 2. The Physical object : a mechanical dipole

From this definition, a physical object describes itself in terms of a relation linking a couple of dual variables, one being intensive, the other extensive - for example forces and positions - that may be described as O(P,F) = 0, where the function O, that represents the object, has the status of a transfer function.

Such an object may be represented in the form of a dipole. The system made up by man and an object is of the same nature as that constituted by 2 objects. Man, when able to manipulate an object, is therefore also representable as a mechanical dipole (figure 1).

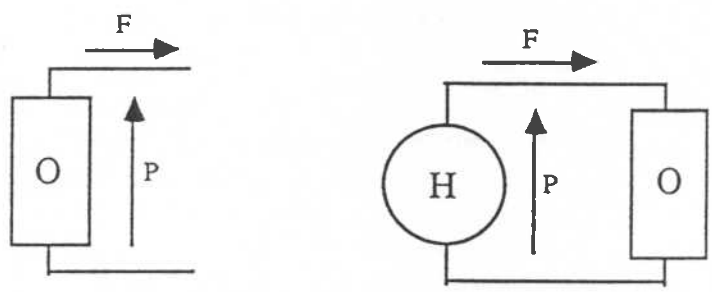

Figure 1 - The physical objet as a dipole

An object or scene made up of objects, is represented by an assembly of dipoles.

Some properties of the physical object

1. Economy of representation

In contrast to the usual phenomenological representations in computer animation, time is not an explicit variable in the definition provided in this instance. The O function codes a piece of structural information. All potential movements of the object are hidden within this structural information and are effected according to these inputs. In the strictest sense the description of movements is absent, for the object is interpreted as a class of movements. By encapsulating this structural information in the model of the object in a way that is independent of temporal instantiations, a degree of economy of representation is achieved.

2. Economy of Control

This structural information plays its part in output flow adaptation. From a quantative point of view, the quantity of information produced on output is higher or equal to that supplied on input. Economy of control is achieved.

3. Generic and generative attributes

This type of description thus provides access to a generic definition of movement.

The physical object or the physical model - is generic for it represents a set of instantiable movements. In contrast to a geometric model or object, even of the actor type, that moves under the control of an outside motor that generates its trajectories or action plans, the physical model or object is "generative" since it is its own motor.

II.3. The difference between the real object, the physical object and the physical model

We have discussed three notions that we must now distinguish and define : the real or natural object, the physical object, and the physical model.

An object, be it natural or real, is an object that is perceptible and may be actuated by man according to various perceptive and actor modalities. A physical object is a sort of real or natural object if we keep within the limits of the usual sensori-motor modalities : sight, hearing, gestual action and tactilo - kinesthetic perception.The above definition includes and integrates the case when artificial sensory motor machines for measurement or action are interposed between man and the object.

The model is a relative notion. The physical model is the conceptual and/or material process that enables production of a real object that is analogous to another real object known as the reference object. To evaluate the model is to compare the 2 objects, one produced by the model, and the other from the reference. In the case of informatics, a model may be, on the one hand, the conceptual process required in representing a reference object, or, on the other, the programmes that carry out this representation. In this instance, these 3 notions - real reference object, model, simulated real object - are made evident by the fact that these programmes can produce, via simulation, another real, perceptible object that can be actuated.

Hence, we can simply state that both the reference object and the simulated object derived from it, are physical objects, since both are perceptible and operable. The physical model itself, is the bridging process between both. It can be broken down into a conceptual model and an algorithmic model. The model is said to be physical if it produces a physical object during its simulation phase (Figure 2).

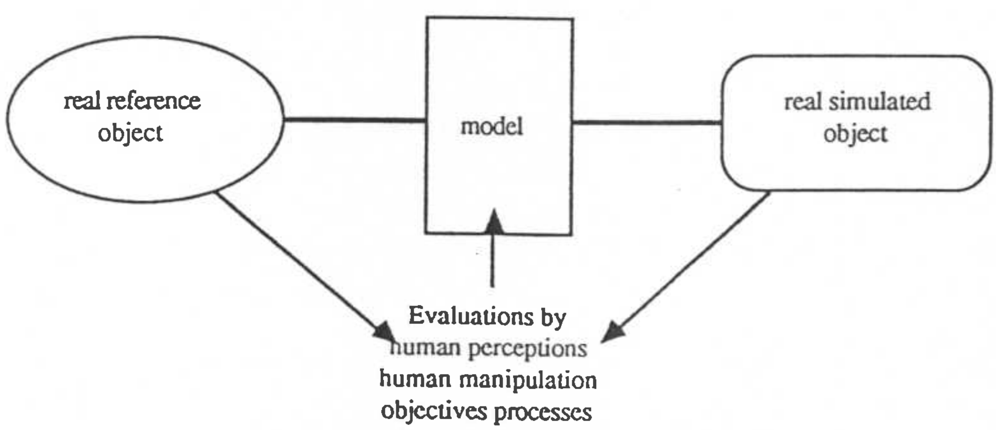

Figure 2 - Reference object - physical model - simulated object

The use (i.e. application) of the model is defined by the evaluation criteria of the proximity between the physical reference object and the physical object produced. The former are closely associated to the idea of the model.

III. Modeler - simulator of physical objects

In our opinion, building a "modeler - simulator" requires 4 stages :

1. Selection of a modelisation principle.
2. Formalisation of the nature of the "components" in the simulation and modelisation system.
3. Elaboration of the calculability criteria of these components and of the objects that the former compose.
4. Deduction of the components' assembly criteria, and finally deduction of the field of representable objects derived from the complete set of these 4 principles.

Having situated the calculability criterion with priority over the assembly criterion, the resulting objects will be dynamically modifiable.

III. 1. Types of models

We have isolated 3 types of models [Cad 79, Cad 81, Luc 81, Flo 89] (figure 3)

* The continuous distributed model. This describes the object in the form of a system of partial second order continuous time differential equations

The above is the analytical model from classical physics. Over and above a certain complexity in this system of equations, this model is no longer operational, and thus solutions are to be found by phenomena categories or for specific objects. Numeric calculus methods are associated to these models, and their generality is the inverse function of operationality. These are the major categories of physics and numeric calculus : vibrating systems, articulated systems, the physics of deformable objects (shells, bars, plates), the physics of rigid bodies ... This model is only marginally appropriate in the description of interactions between objects or between material elements.

The above type of model was selected for the research that we have already referred to [Ter 87, Ter 88, Bar 88].

* The continuous localised constants model that constructs a <u>structural</u> discretisation of the object beforehand, i.e. that breaks down the object into components and then supplies a formulation of the preceding type for each component. In this instance, an assembly method (or category of methods) is implicitly contained within the formulation.

The above model is more operational ; Physics, electronics, and automatics use this type of model when the objects to be studied are too complex or too little known to be approached by the first method.

In fact, the constants' localisation principle introduces the notion of "component", and therefore of assembly. This type of model enables objects to be created, by arranging the components, where each of them has a functional description. We interpret this method as a language, in other words as a representation type that gives rise to object creation.

* The discrete localised constants method, that elaborates a structural discretisation of the object, and provides a direct numeric formulation for the behaviour of each component. In this case, the model already implicitly contains a numeric calculation method or category of methods.

This may be considered, as in the preceding case, as an object description language. Moreover, we interpret it as a simulation - calculation language for the behaviour of the particular object.

Because of this, our choice focussed on this last principle of modelisation, and we have set forward the principle of discrete localised constant modelisation as the foundation principle for a physical object simulation and description language.

"Plasticity" and "rupture" are often added to these basic laws.

For given objects, a formalisation in terms of components is possible. For others, physics can only provide a phenomenological approach.

It will be seen that the physics of materials is thus akin to a library of behavioural laws.

Strictly speaking, there is no physics of liaisons. Mechanics may have a liaison typology at its disposal for mechanical technology [Fre 64, Art 77, Bam 81], but dynamics for given liaisons between objects or real materials is lacking.

The standard classification is thus founded on 3 classes, matter with a general law, material with "ad hoc" laws , liaisons described only in some cases.

We cannot select components for a "modeler" without having initially attempted a basic formalisation and classification of the behaviour that is guided by the very terms of the computer / informatic simulation. In this context, we will justify the following classification, based on 3 another classes :

1. Modelisation of matter.
2. Modelisation of the material in its non-discontinuous behaviour,
3. Modelisation of the structure of the material, (of the object, or of the scene). It includes structural consistance or structural modificability, non permanent liaisons, plasticity, ruptures ...

III.2.1. Matter modelisation

We have the choice between particle or solids dynamics. A particle has 3 degrees of freedom, an elementary solid, rigid or not, more than 6. Solids physics is a more compact formulation than that of particle physics, as compactness is the expression of the high correlation between different particles of the solid. The behaviour of a solid may be represented by means of particle physics, with individually simpler equations and, in any case, that are more adapted to interaction calculations. In an informatics context, the "particle" formulation, that is less compact, seems to be more operational :

* since the calculators can carry out simple and identical calculations,
* because these lend themselves more readily to modularity,
* because they are more adapted to a high degree of interaction, and in particular to the outside universe.

As will be shown later, this choice entails considerable gains on both a conceptual and an algorithmic level for effective simulation .

In consequence, matter is discretised into punctual masses with nothing in between (figure 4)

1. The minimal matter element is a punctual mass which has one parameter, m, and 3 degrees of freedom. 3 forces, can be applied to it, and it supplies 3 positions by means of the equation F = M.G, which can be expressed in terms of finite differences. The calculation is easily vectorised on 3xN vectors, N being the number of masses.
2. The component is presented as a dipole (F,P).
3. It can be observed that it is an elementary physical object, which is simulable, calculable, and manipulable.

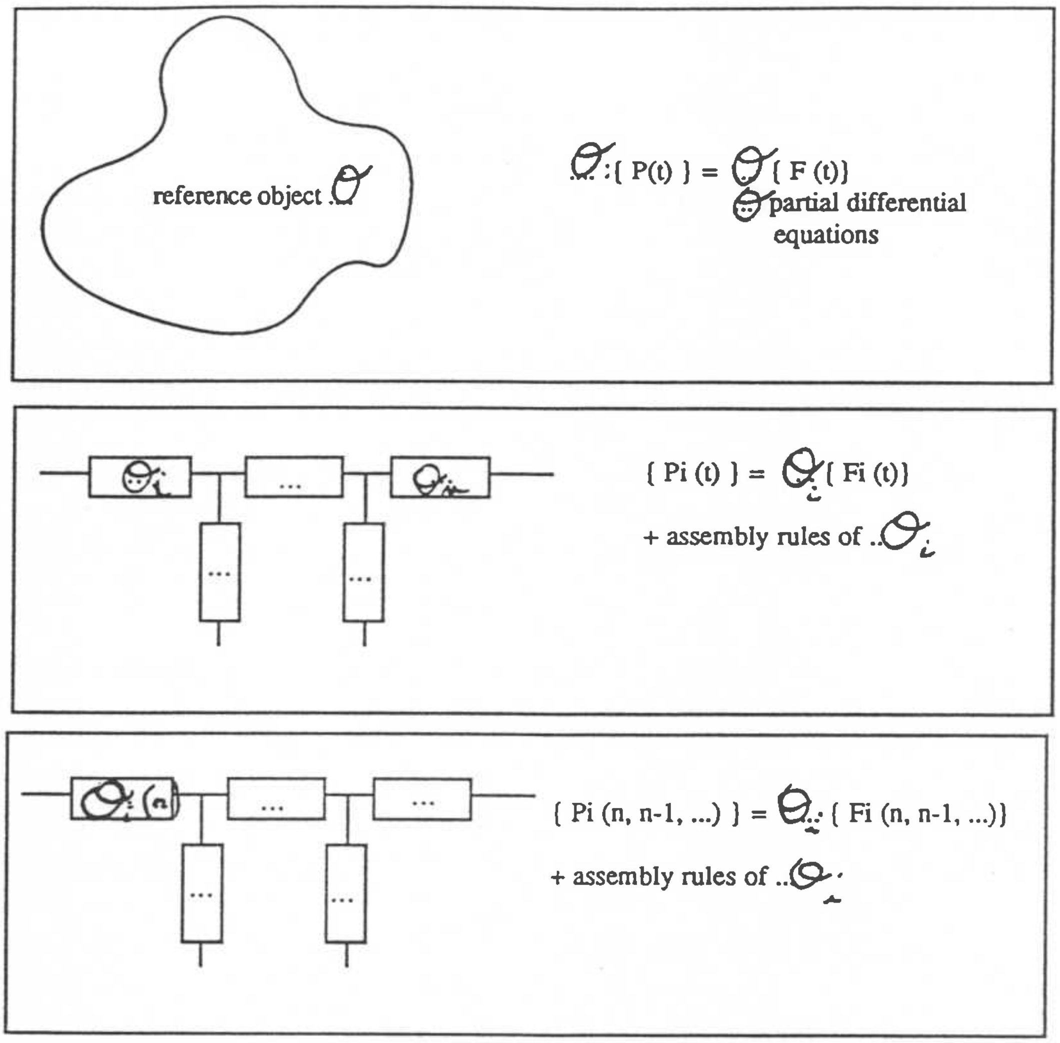

Figure 3 - Three types of physical models

III. 2. The choice of components

In classical fashion, the distinction must be drawn between "matter", "material", and "liaisons" [Bam 81]

Matter behaviour is described by the fundamental dynamics equation :

in a simplified form : $\{\vec{F} = \int m\vec{G}\}$ for particle physics

$\{\vec{F} = \int dm\vec{G}, \vec{M} = \int dm.\ \vec{OM} \wedge \vec{G}\}$ for solids physics.

The two regulate the question of "the quantity of movement".

Material behaviour is described by non-generalised laws. The latter regulate the "quality" of the "movement". Hence, a wooden stem or rod does not behave in the same way as a rubber one, and water does not flow like oil does.

The most usual behaviour can be represented by basic rheological laws pertaining to "elasticity" and "viscosity". By combining the latter we can obtain primary behaviour sets such as the Kevin - Voigt and Maxwell models ..., and then by subsequent combination, obtain the behaviour of standard objects [Bam 81].

"Plasticity" and "rupture" are often added to these basic laws.

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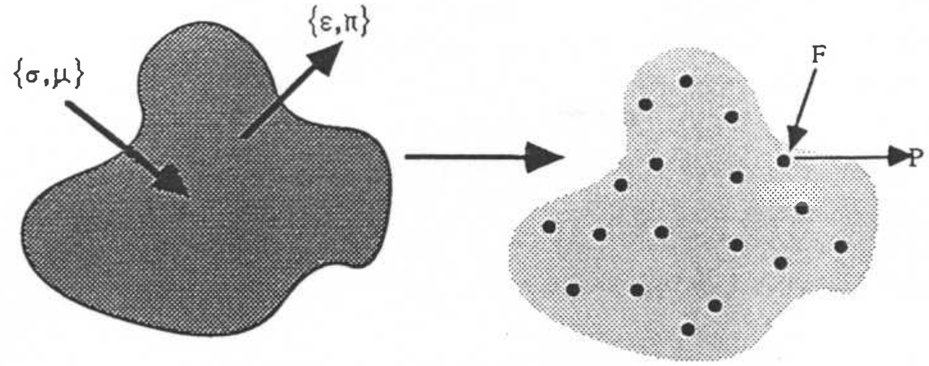

figure 4 - Matter representation

III. 2.2. Modelisation of the material in its continuous behaviour

We shall only retain here the 2 basic rheological behavioural states. These are elasticity and viscosity, which are characterised respectively by the bijective functions : Forces = f (Positions) and Forces = f (Speed). These functions may not be linear. Their basic version is the linear function of respectively parameter K (stiffness) and Z (viscosity). (figure 5)

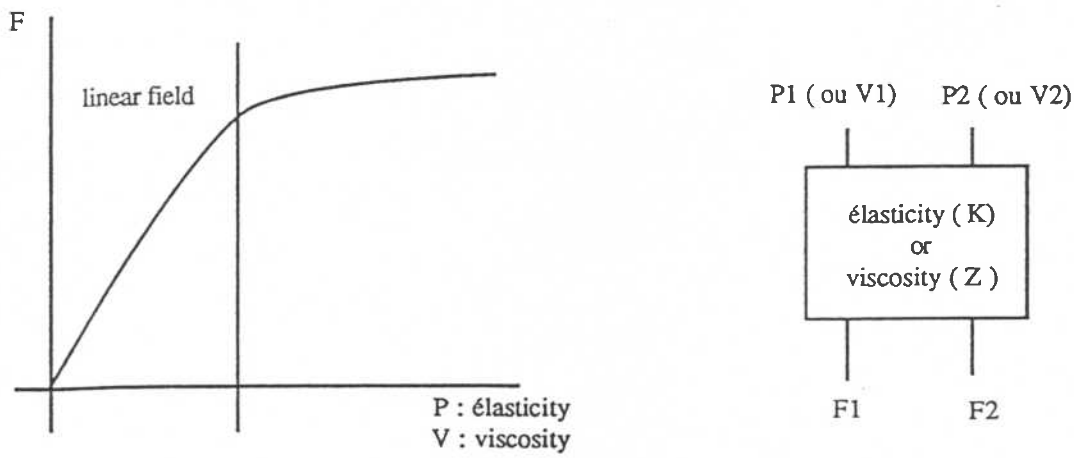

figure 5 - basic rheological functions

Elastic behaviour brings about reversible evolutions. Most solids have elastic behaviour under low constraint. Fluids at constant temperature have elastic behaviour.Viscosity behaviour is an irreversible transformation.

All linear behaviour as well as continuous non-linear behaviour may be represented here.

The base components, that can be located by the "spring" and the "damper", are present in quadripole form {(F1,F2), (P1, P2)}

Plastic behaviour, that is often presented as a basic rheological function brings about a hysteresis. We do not consider it as a basic component of the material, and we shall examine it later.

III.2.3. Modelisation of the structure of the matter and of the objects.

The components that enable modelisation of the material are equipped with 2 "non-physical" logical functions.

* One serves to "link" the mass components together
* The other is to effect this liaison according to a transition state logic, so as to modify the parameters of the material in function of conditions over the values of the physical variables.

The first function enables us to describe the matter or an object as an interconnected network of components.

The second allows us to modify the form of this network dynamically (figure 6).

If we can modelise the commonest objects, and solids in particular, by linear and continuous behaviour, this is not the case for interactions between objects or for interactions between simulated objects and external objects. A general formalisation of the different interaction categories is of prime importance, whether on the microscopic level of matter, or macroscopically as in a scene or for an object :

* permanent interactions - definition of the cohesion of an object or of a material
* temporary interactions : plasticity, rupture, shocks, sticking, grasping actions ...

The general formalism is the following (figure 6):

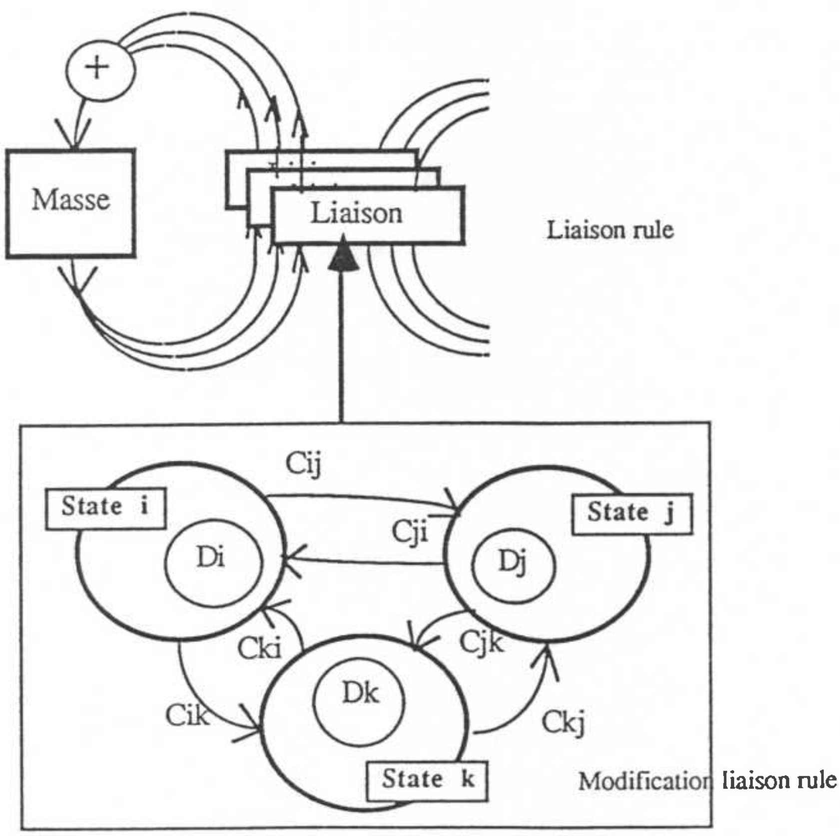

figure 6 - Material, object and scene modelisation by interactions

a. formalism for inter-connection

2 punctual masses are linked by a given number of friction or spring type components in parallel. This is also true for entire sets of punctual masses.

Objects are linked in the same way, and since any object is described in terms of particles, it follows that these liaisons will also be punctual.

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b. formalism to modify the liaison

In addition, each preceding liaison is defined by :

* a state describer with a label

* the state change conditions

The state describer provides the values of the physical parameters (stiffnesses, viscosities, ..., threshold values).
State change conditions are logical operations on all the physical variables as "increase, greater than, equal to ..."

III.2.4. Examples

1. Collision, sticking, plucking or grasping action

Collisions are normally processed by a calculation method known as "penalty method" which is an approximation of the resolution method of a hyperstatic system by the Lagrange multiplier [Pla 88, Dum 89]

The Lagrange multiplier method processes the adjunction of a contact liaison in two initially independent physical systems. When interpreted in terms of a model, this method essentially adds a spring of strong stiffness K between the 2 objects that come into collision at the shock point. Thus it is implicitly a dynamic modification of the structure of the scene : a component appears and disappears according to a condition on the status variables. The contact is modelised by means of a high value stiffness elastic liaison.

Hahn [Hah 88] generalises this method by defining this method as elasto - viscous. The dynamic of the solid complicates its formalisation since it entails distinguishing between collisions with or without sliding and selecting an empiric direction of the forces during the shock.

Our formulation takes all these cases into account. It also considers many others that are left to the acuity of the scenes' conceptor, on the stage of the scene's design by the unique and explicit formalism, which is the addition - suppression of a component, whatever its nature , in function of explicit conditions over the state variables, whatever they may be. These conditions concerne positions for simple collisions, but also speeds or forces ...

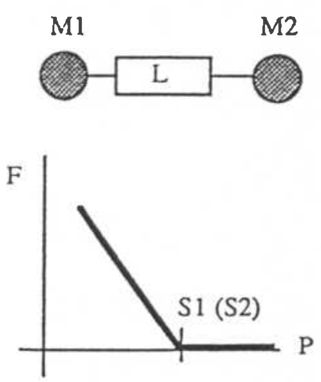
In fact, a collision is a particular case of temporary liaison.

Figure 7 describes the modelisation of an simple elasto-viscous collision with conditions over positions.

The grasping action is modelised as a collision without a return to the initial state.

The plucking action is modelised as a two-threshold collision.

Sticking is a variety of the grasping action.



L : STATE1 := (K=0, Z=0, D=?,V=?)
STATE2 := (K=Kc, Z=Zc, D=Dc, V=Vc)
Condition (D, S1, S2)

Collision	STATE1 : D < S1 , -> STATE2 STATE2 : D > S1 , -> STATE1
Grasping	STATE1 : D < S1, -> STATE2
Plucking	STATE1 : S2 < D < S1, -> STATE2 STATE2 : D > S1 ou D < S2, -> STATE1

figure 7 - Collision, grasping, plincking, sticking

2. The collophane effect and the ratchet effect

Bowing friction, or the collophane effect is a far more complex case, for it is a question of a drive liaison between 2 bodies, where one is in periodic movement, and the other is a linear movement. The liaison is regulated by hooking cycles when object 1 drives object 2, and of unhooking, when object 2 is free [Cad 81, Cad 83] [Flo 86]. The hooking - unhooking condition concerns the relative speeds of the 2 bodies with reactualisation of the relative distance between the hook-up points. The liaison is modelized by a conditional spring - stiffness component:

$F = K. Lr - Z.V$

$Lr = L - La$, L is the élongation of the spring, La is its elongation at the rest

V is the relative speed between the 2 objects

State1 (hooking) : $K = Kh, Z = Zh$

$Lr > Lr0$, -> State2

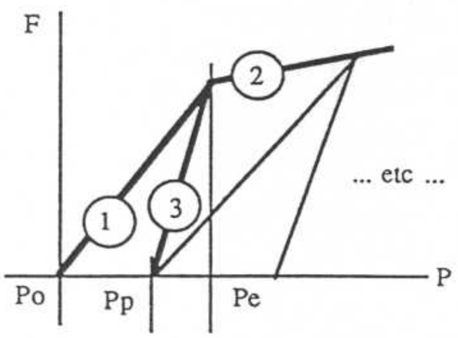
State2 (unhooking) : $K = 0, Z = Zunk$

$V < V0$, -> State1

The ratchet effect is of this type but the condition here concerns the relative positions [Flo 78, Flo 89].

3. Plasticity and "écrouissage"

An elastic material may present a constraint threshold, known as plasticity, beyond which permanent deformation appears. The "constraint - deformation" law presents a hysteresis (figure 8). The "écrouissage" may be described by a cyclic multi-state plasticity model that extends up to break point .



Pe : Elasticity threshold
Pp : Plastic remanent deformation

STATE1 : K1, Z1, Po
P < Pe, -> STATE2

STATE2 : K2, Z2, Pe
P < Pe, -> STATE3

STATE3 : K3, Z3, Pp
P > Pe, -> STATE2

Figure 8 - Plasticity - "Ecrouissage"

II.3. Conclusion - Comparison "particle dynamics / solids dynamics"

We use this formalism to deal with all cases of non-permanent liaisons between the different components of the object and the matter.

This general interactions formulation pinpoints the close proximity that exists between collisions, plasticities or frictions of the "collophane effect" relaxation type, or more simply actions of grasping, splitting, unhooking or unsticking.

Therefore, within this context, collisions appear as modifications of the dynamic structures of the scene, which comes to the fore as the fundamental problem. For one thing, there are thus no special "collision" algorithms, even though this system is especially adapted to their calculation. Another point is that collisions, in our opinion, appear as the simplest interaction cases after the grasping action.

In fact,- the physical particle formulation, is more relevant to expressing and calculating microscopic or macroscopic interactions than the physics of solids. We can remark that :

1. From a matter modelisation standpoint, the 2 formulations are equivalent.

2. In the case of the modelisation of material, i.e. the non discontinuous interactions between elements defining a single body, the "particle" formulation is more convenient.

In distributed models, the relation between the constraints σ and the deformations ε is expressed at infinitesimal level by $\sigma = \mathfrak{R}(\varepsilon)$. σ and ε are 6-component tensors. They characterise the deformations and constraints following 3 compression / extension axes and 3 torsion axes of the elementary solid .

When this formulation is applied to a more macroscopic element, for example a mesh element, the $\mathfrak{R}_{mesh}$ associated to this element must be calculated by the integration of the preceding infinitesimal $\mathfrak{R}$. It should be noted that $\mathfrak{R}$ are complicated mathematical objects (a matrix of 6 * 6 in even the simplest cases). Their formal manipulation and also their algorithmic transcription are unwieldy.

In the "particle" formulation, the elements in play are univariable. The notions of applied constraints / deformations applied to a mesh element are replaced by those of forces and displacements that apply to punctual masses.

3. In the case of interactions between mobile objects, the difference is even more striking. In the "solid" case, the objects are defined by positions and shapes and, if need be, their derivatives. The calculation method of the force system is generally in two stages :

* detection of the contact zones
* calculation of the forces.

These calculations are unwieldy, and inextricable if the interaction zone is multidimensional. In particular, often the direction of the forces cannot be calculated. In this method, when one arrives at this point, one limits to a punctual interaction zone or to a specific orientation of force.

In the "particle" formulation, each mobile object, that is modelised by a set of points, gives rise to P * Q univariable central force interactions. The only difficulty is multiplicity, but this is only a slight drawback when compared to the high degree of simplicity and the broad generality of the method, which may applied to all forms of objects, be they deformable or not, with any interaction zone.

III. Calculability

We must avoid a return to writing out a complete system of differential equations or of finite differences commanding the system, but rather to observe under what conditions the entire set of components defined above, and interconnected to create a scene, is calculable from the equations for each of the components.

We must, therefore, choose a calculable formulation for each of the components, so that this is compatible with the modularity.

The equations associated with the components, are, for the moment, non oriented. We should orient these equations so as to enable association of the physical components defined so far, with the calculation-components, that are themselves connectable. This supposes defining inputs / outputs on each component, so that the outputs from one component may be connected to the inputs of another.

To do this, a propagation direction must be introduced between variables of a different nature :

If we describe the "mass" component an oriented dipole P -> F, the liaisons will be described by the oriented quadripoles (F1, F2) -> (P1, P2), and vice - versa (figure 9).

From an algorithmic point of view, the system calculating an object appears as a 2 phase system. The first, where all the current forces are calculated from the current positions, and the second where all the current positions are calculated from the preceding forces (figure 9).

The calculation for each element can then proceed according to different methods, of which the simplest and quickest is the finite differences method [Cad 79, Cad 81, Luc 81, Flo 86].

Remark : Most of physical models for images based on a distributed constants model (model type 1), resolve the complete system commanding this model by numeric calculation methods that implicitly introduce this functional dissymmetry of the dual variables. Bringing this orientation explicitly to the model level, means that the simulated object will explicitly be constructible, without any extra hypothesis.

IV. Assembly

We thus have at our disposal, "components to connect", the masses, and "components for connection", the liaisons (figure 9).

An object is a network that is made up from these elements, according to a simple assembly logic. (figure 16) :

* The nodes are the "mass components".
* The arcs are the "liaison components".

This description in network of an object or of a scene, on a variables level, means an application of the laws of Kirchoff (figure 9)

* the intensive variables have their sum nul in a node,
* the extensive variables characterise a node.

The Kirchoff laws are deducted from operations like series - parallel transformations, which enable equivalent networks to be defined. This is one of the major advantages of this formalism.

In this way the basis has been set out for a modeler and its simulator that are granted an extra property, which is to be able to build other functionally equivalent structural models from a specific model of a scene.

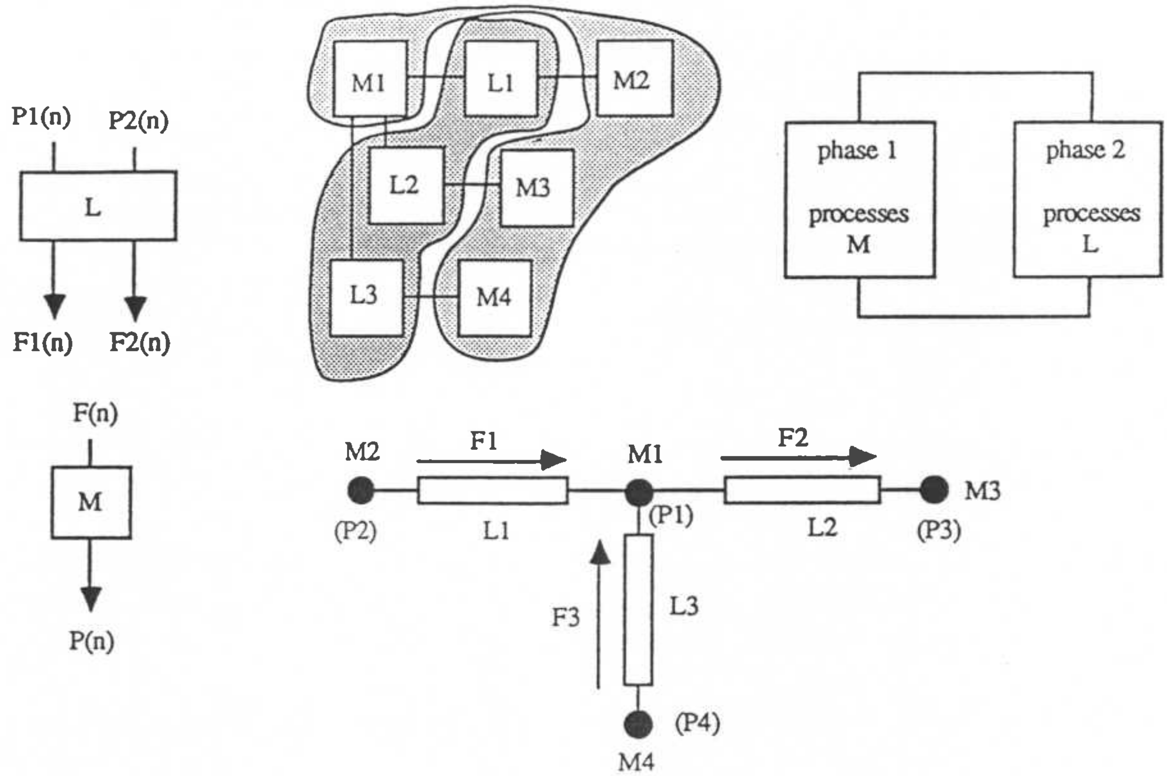


Figure 9 - Calculable and combinable components

IV. Introducing multitude behaviour

In the modelisation proposed here - physical particles and atomiques interactions - there is no basic difference between a solid, a gas or a fluid. The difference is only on the number of particules and the number of interactions calculations.

An extension of the formalism describes above has been implemented [Jim 89]. It consists in :

1. generalizing the ponctual particules by a spherical particule. This, named "ball", is a ponctual physical particle, with three degrees of freedom, surrounded by an impenetrable apheric zone. The forces applied on the ball are always centred forces.

2. extending the interaction function between particles by a generalized interaction function between sets of non-labeled particules. In this way, we defined blocks of matter named "agglomerates".

The main properties added by these extensions are :

1. The models are optimized in the way that they take into account physical specificities of objetcs as, for example, the depth or the local area of deformation.

2. The topology and consequently the shape of the objects are not predefined, but are the result of the dynamic process ant correspond to an equilibrium state of the physiqcal system.

3. This topology and this shape are dynamically controlable. This permits sticking and fractures simulations (see photographs).

V. Outside communication

V.1. Force feedback gestual transducers (f.f.g.t.)

When a physical object is manipulated, man may equally be assimilated to a physical object, and represented by a mechanical dipole, either in providing positions and receiving forces - when he is equivalent to a "mass" component type, or the opposite - whereby he is equivalent to a "liaison" type component.

This regulates the functional communication between man, or any other outside object to this simulated universe, and this simulated universe.

Physical communication entails the introduction of specific transducers to enable communication of forces and positions in both directions, from the outside to the simulated universe, and the contrary.

These physical systems are devices that integrate sensors and motors within a specific morphology . These sensor - motor systems are therefore "acting - perceiving" sytems. Through them, man can manipulate and act on simulated objects, and simultaneously perceive their behaviour in a tactilo-proprio - kinesthetic manner.

Florens [Flo 78] introduced the first f.f.g.t. device and the first associated physical simulations, and in particular ratchet or chocks simulations.

" Computing with feeling" by Atkinson [Atk 77] also describes the principles of a 6D feedback device.

Cadoz - Luciani - Florens (81) presented a second f.f.g.t. device, that was more efficient in terms of power, compactness, and speed. This was the piano key named "Feedback Touch".

The photograph (1) represents the new device built by Lisowski - Cadoz - Florens [Lis 88, Lis 89] named "16-slice-Feedback Touch".

This is a keyboard actuator, with 1 to 16 keys in its present form, and each key is 13.75 mm thick. It has been devised for manual gesture, and offers simultaneously :

* Multidimensionality. Up to 12 degrees of liberty to grasp or manipulate a simple object.
* A low displacement range of around 3 to 5 cms.
* Instantaneous power which can be high as in the case of percussion on a surface.

Furthermore, this device provides double modularity

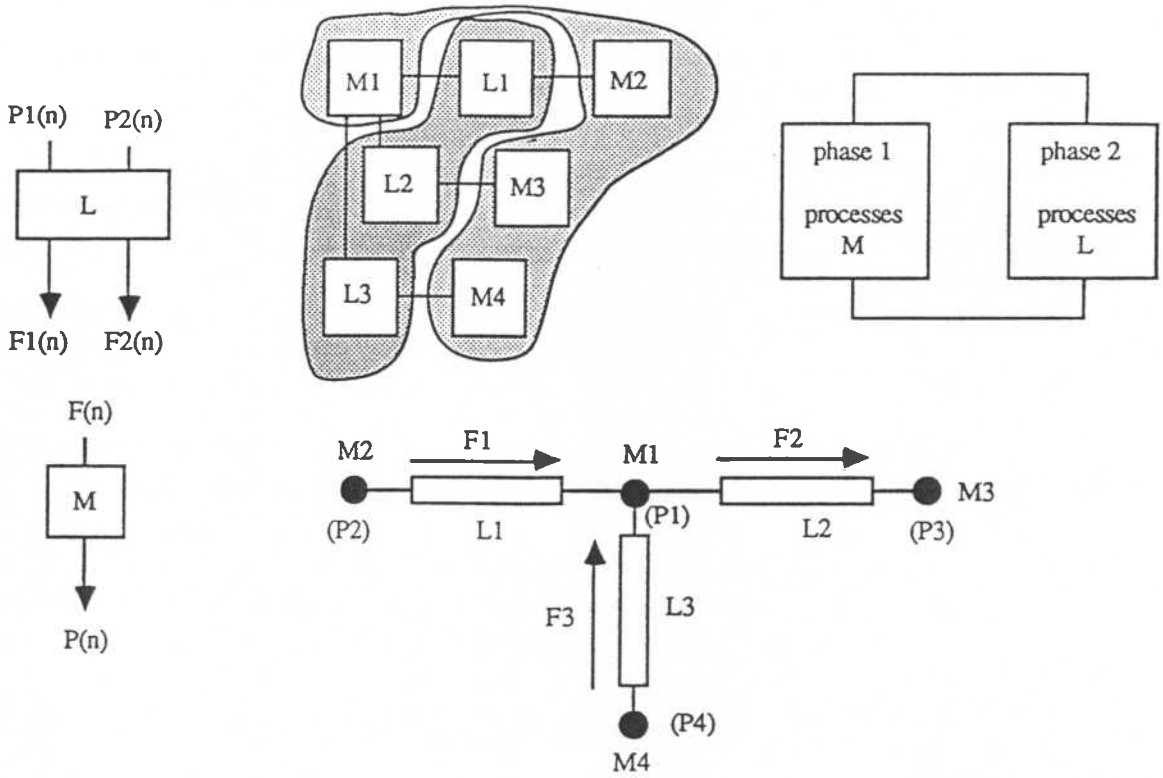
* Electromechanical Modularity : the motor principle alows keys to be added on or suppressed.
* Mechanical Modularity : The mechanics of the actuators has been designed to receive mechanical interfaces that enable special morphologies of the manipulated device to be defined.

A specific morphology to manipulate flat objects has been connected. This new f.f.g.t. is named "Two-thimbles", ("Dés-2D in french). By sliding your fingers in the two rings, objects can be grasped, dragged, or compressed. Moreover, their reaction can be felt, for instance their resistance to deformation or displacement.

<u>Example</u> : Moulding Plasticine piece with the "two-thimbles"

A piece of plasticine has been simulated with an agglomerate stabilised with a Van der Waals interaction function.

This piece presents a plastic behaviour (see photographs). It remains in the mouldable shape. The operator knead the paste with the f.f.g.t. "two-thimbles". He can tears the paste to several pieces. He can also re-sticking them .



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V.2. Real time visualisation synchroneous with the action

Two real time sensory loops are required to manipulate an object. One is to associate the gestual action to the tactilo - proprio - kinesthetic perception, and the other associates the gestual action to visual perception.

The model of the object must therefore function overall at a speed whereby the gap between the action and the 2 resulting perceptions is imperceptible.
The actions are sampled between 25 Hz to 1 Khz. The calculations are carried out at this speed.

All examples shown in this article are generated at this speed.

The computer architecture is highly efficient : a set of dedicated machines of the vectorial processor type function in parallel.

VI. Simulation examples

From these principles we have created a great deal of physical scenes.
We show below some examples :
* High or dense multiplicity scenes (photograph 6). A very large number of elementary physical objects interact with each other and with fixed elements. Turbulences, vortexes, and the constitution of structured clusters may be found.
* Rigid, plastic and déformable objects (photograph 2, 3, 4) in interaction with their environment or with the operator who manipulates them in real time and perceives them through touch and sight.
* Complex multi-object scenes of all preceding types in interaction, collage, or rupture (photograph 5) ...

VII. Final Notes

A film is available to show simulations for each of the categories.
All the simulations are in real time, e. g. the calculations are effected between 25 Hz and 1500 Hz, according to the frequence stability of gestual control loop.

The entire system, named CORDIS-ANIMA system, equipped with a language, a simulator, the gestual peripherals, and real time display constitutes a really genuine tool for building, experimenting and perceiving that entity , described in the words of Foley [Fol 87] as "**an artificial reality**", or if we prefer, "**a physical illusion**".

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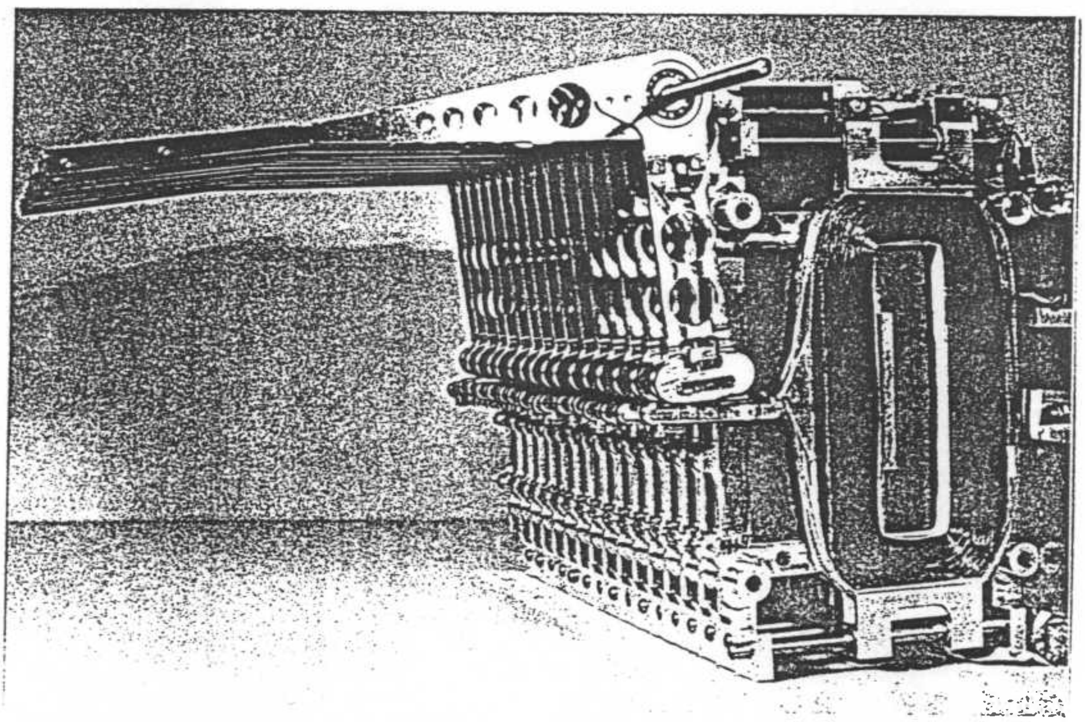
IX. Photographs

Photograph 1 - The "16-slice Feedback Touch"



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Photographs (continued)

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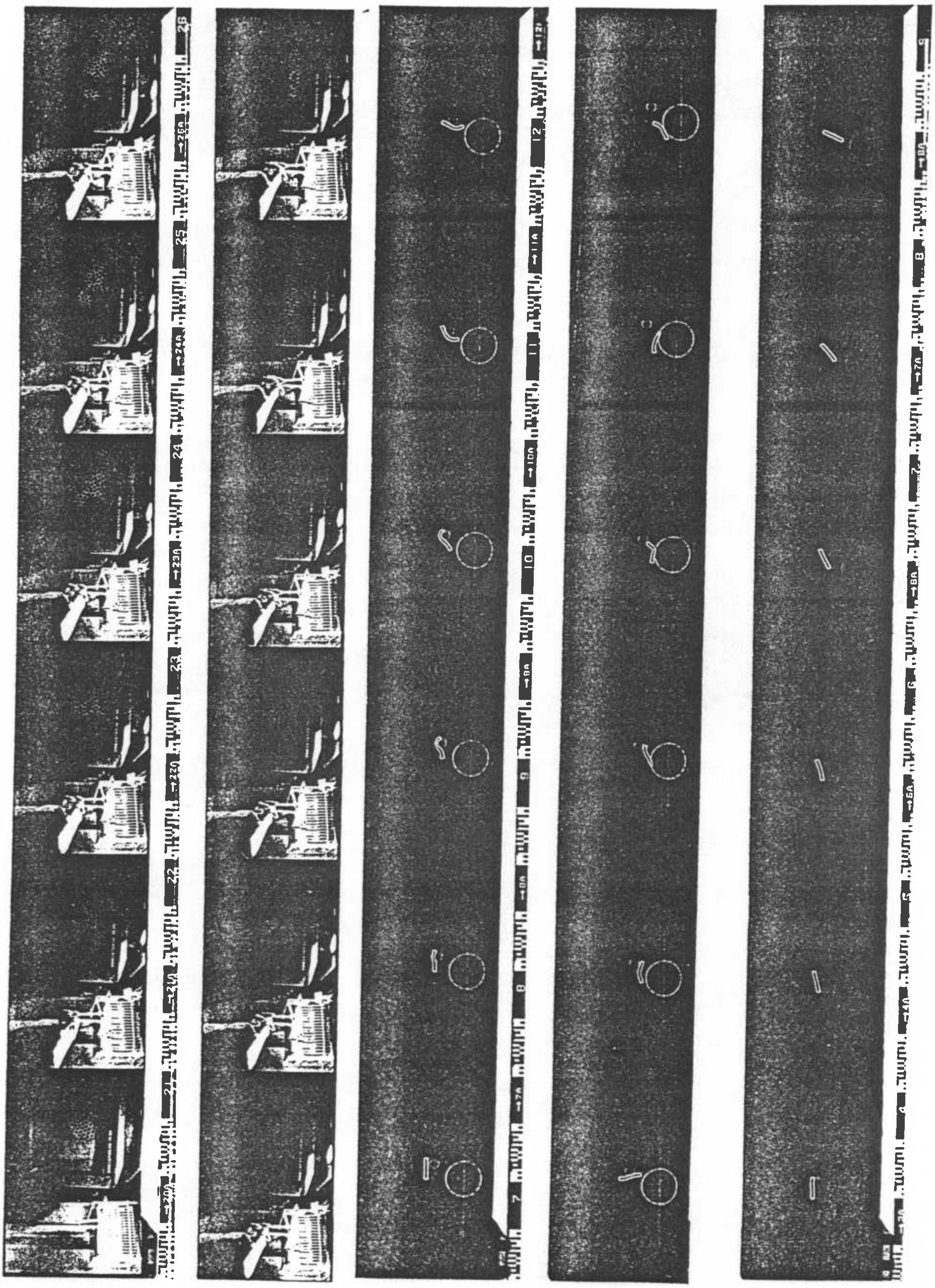

Photographs (continued)

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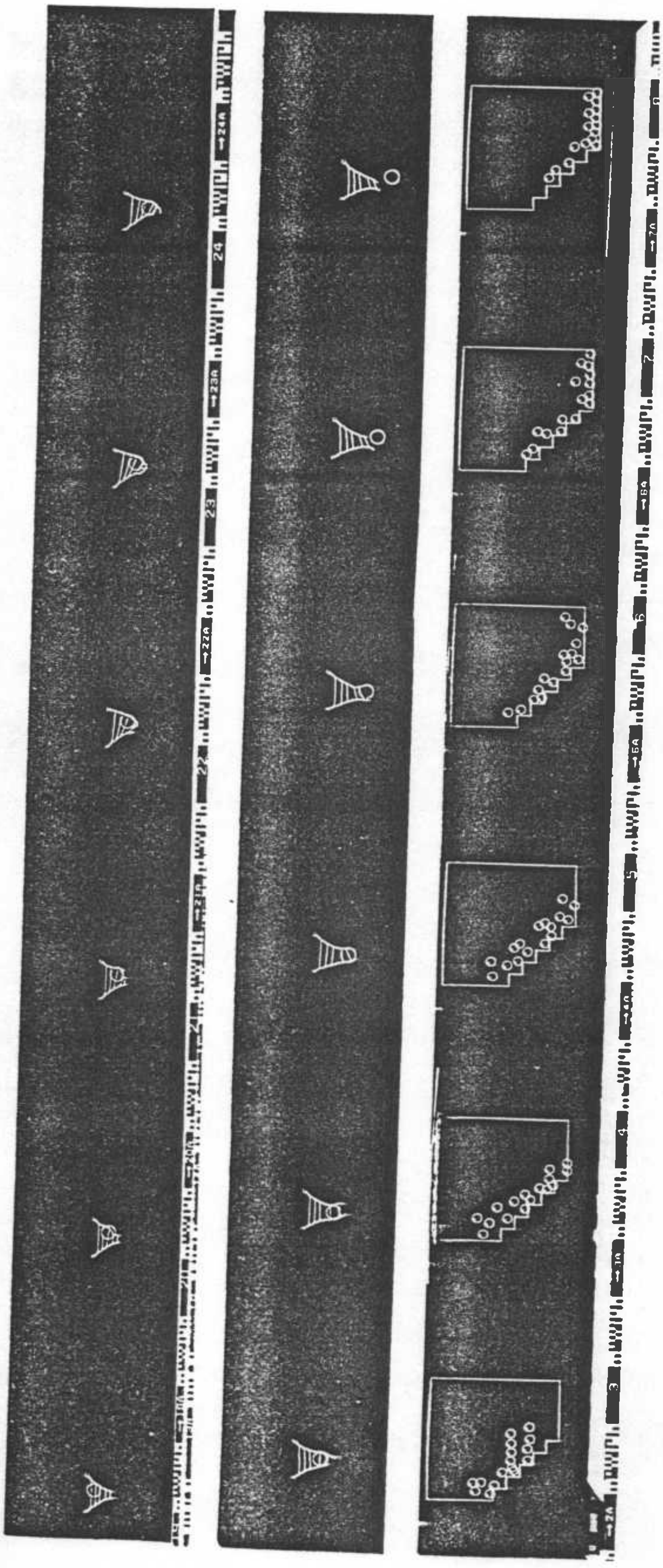

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Photographs :

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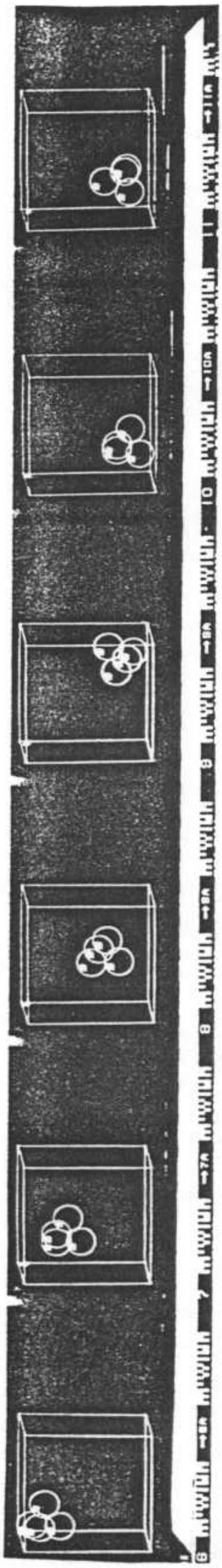

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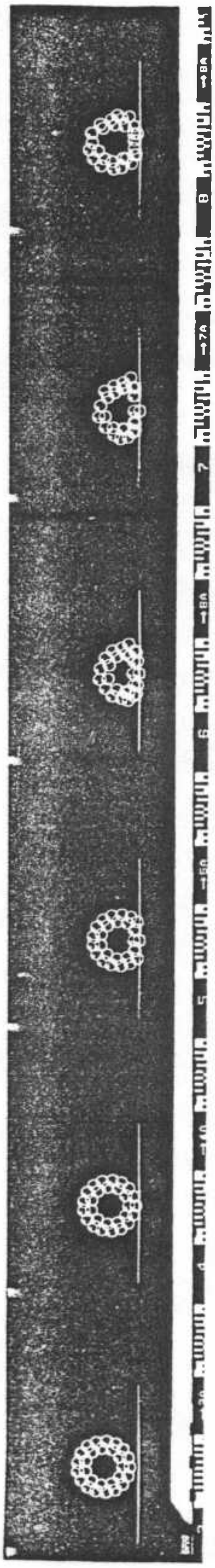

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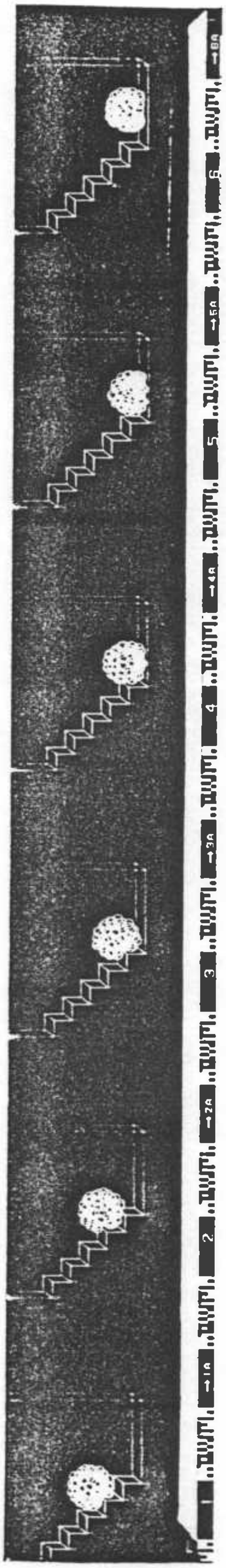

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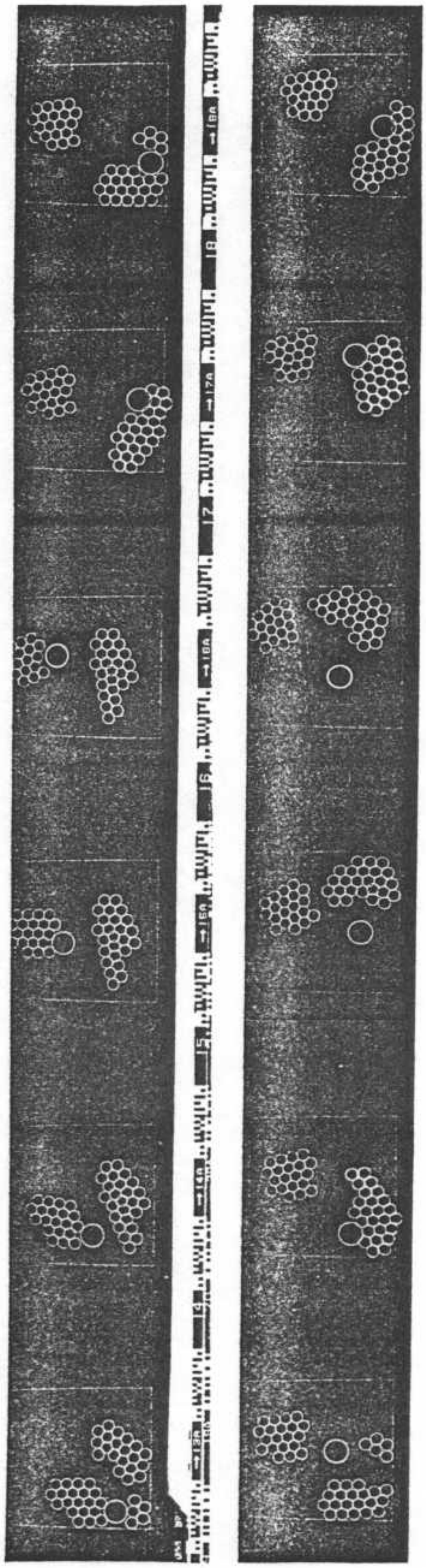

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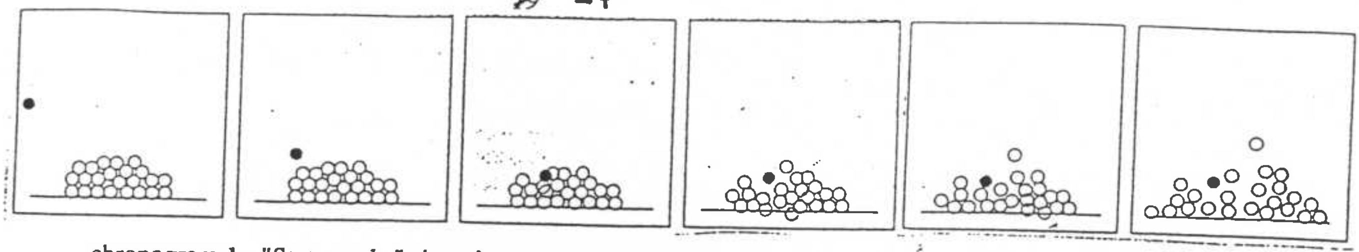
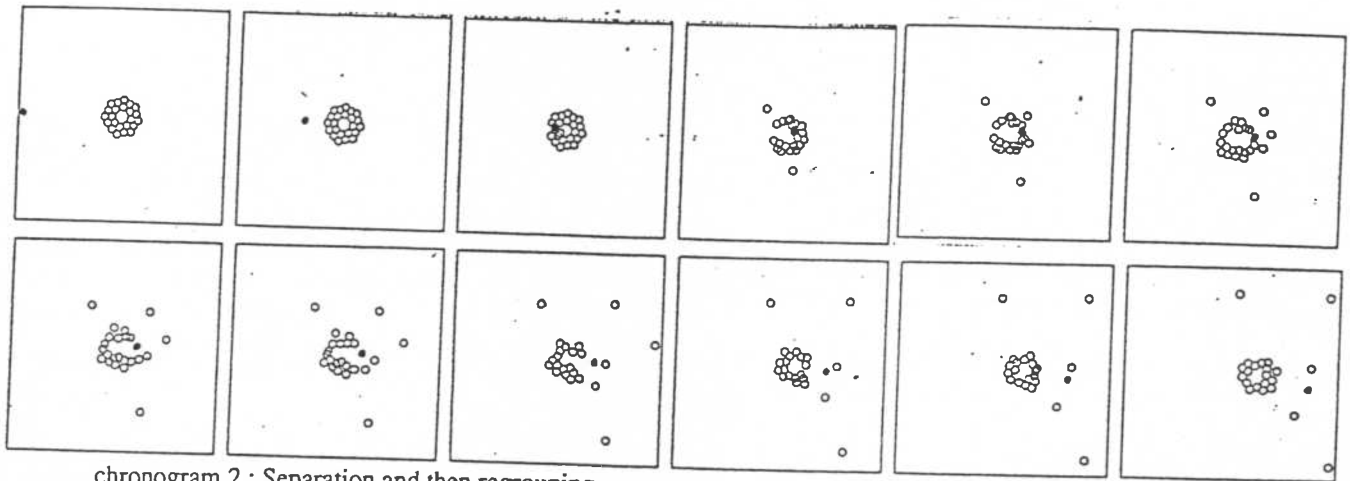
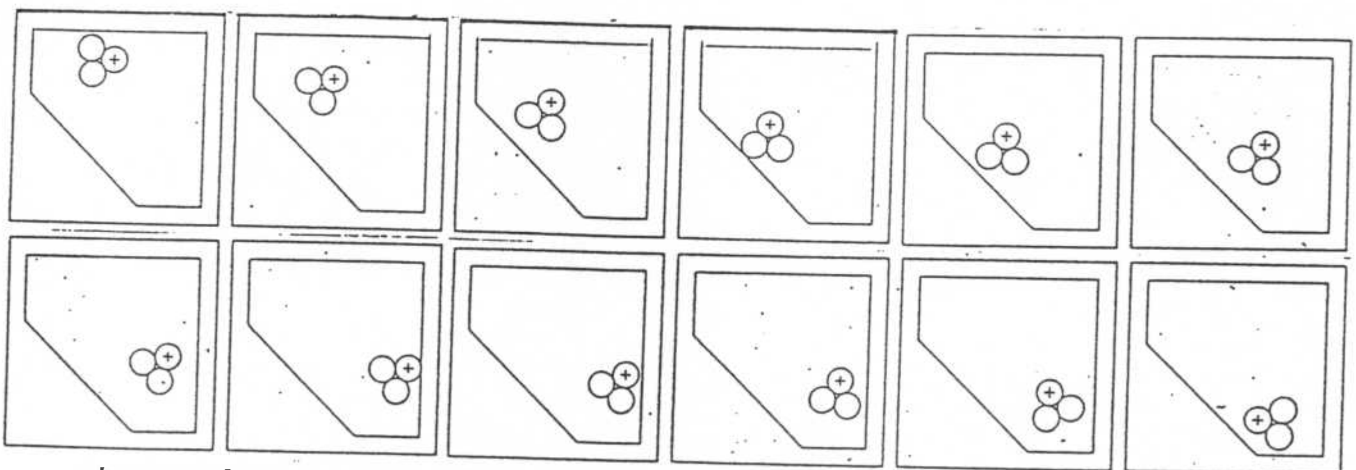


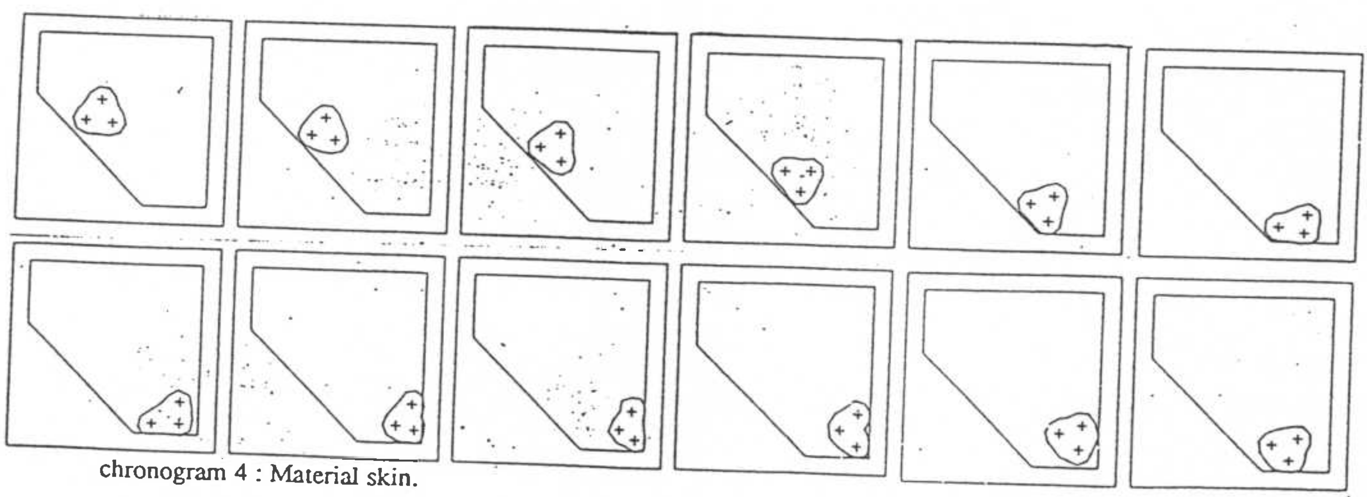
chronogram 1 : "Statt stacks" shatering.



chronogram 2 : Separation and then regrouping.



chronogram 3 : An elementary solid.



chronogram 4 : Material skin.